NOV 1 6 1989

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WAVES AND PULSED LASER PROPULSION

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1998 0513 147

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U02114

Accession Number: 2114

Publication Date: Jul 17, 1989

Title: Laser-Supported Detonation Waves and Pulsed Laser Propulsion (preprint)

Personal Author: Kare, J.T.

Corporate Author Or Publisher: Lawrence Livermore National Laboratory, Livermore, CA 94550 Report Number: UCRL-101677

Report Prepared for: U.S. Dept. of Energy

Comments on Document: Prepared for the 17th International Shockwave and Shock Tube Symposium, Bethlehem, PA, 17-21 July 1989.

Descriptors, Keywords: Pulse Laser Propulsion Rocket Thrust Design Propagation

Pages: 006

Cataloged Date: May 23, 1990

Contract Number: W-7405-ENG-48

Document Type: HC

Number of Copies In Library: 000001

Original Source Number: DE90-0002753

Record ID: 21051

Source of Document: NTIS

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LASER-SUPPORTED DETONATION WAVES AND PULSED LASER PROPULSION

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ABSTRACT

A laser thermal rocket uses the energy of a large remote laser, possibly ground-based, to heat an inert propellant and generate thrust. Use of a pulsed laser allows the design of extremely simple thrusters with very high performance compared to chemical rockets. The temperatures, pressures, and fluxes involved in such thrusters (10^4 K, 10^2 atmospheres, 10^7 w/cm^2) typically result in the creation of laser-supported detonation (LSD) waves. The thrust cycle thus involves a complex set of transient shock phenomena, including laser-surface interactions in the ignition of the LSD wave, laser-plasma interactions in the LSD wave itself, and high-temperature nonequilibrium chemistry behind the LSD wave. The SDIO Laser Propulsion Program is investigating these phenomena as part of an overall effort to develop the technology for a low-cost Earth-to-orbit laser launch system. We will summarize the Program's approach to developing a high performance thruster, the double-pulse planar thruster, and present an overview of some results obtained to date, along with a discussion of the many research questions still outstanding in this area.

INTRODUCTION

Laser propulsion, proposed originally by Kantrowitz[1], and since studied by a variety of researchers[2], uses a large fixed laser to supply energy to a distant rocket vehicle. The laser beam heats an inert propellant, which is exhausted to provide thrust. Because the propellant exhaust velocity is not limited by its chemical energy content, laser propulsion thrusters can provide exhaust velocities several times higher than chemical rockets.

Following a 1986 SDIO/DARPA Workshop on Laser Propulsion[3], the SDIO (U.S. Strategic Defense Initiative Organization) has supported a research Program in Laser Propulsion. The goal of this Program is to develop the physics and technology needed to launch payloads from the Earth into orbit using large ground-based lasers. A laser launch system should be inexpensive to develop and operate compared to conventional rockets because most of its hardware remains on the ground. However, to be economical, such a system must launch many small payloads — up to 30,000 20 kg payloads per year for a minimum-sized system[4] — and thus requires an extremely simple, lightweight vehicle and thruster. The SDIO Program has thus concentrated on one such thruster, the double-pulse planar thruster, which is described below.

The SDIO Program includes theoretical and numerical modeling of laser propulsion thrusters and vehicles. It also includes small-scale experiments using single pairs of laser pulses at energies of one to several hundred joules. Several university groups, two national laboratories, and three industrial laboratories have contributed to the Program to date.

(The figures of merit for rocket thrusters are specific impulse, or exhaust velocity [$I_{sp} = v_{exh}/g$, where g is 980 cm/s^2], and thruster efficiency, defined as

$$\eta_{thr} = \frac{\frac{1}{2}\dot{m}v_{exh}^2}{P_{thr}} \qquad (1)$$

where $\dot{m}$ is the mass flow in the exhaust, and P_{thr} is the average laser power reaching the thruster. These are related to the more common laser-impulse measures of coupling coefficient C_m and specific ablation energy Q^*, by $\eta_{thr} = \frac{1}{2}C_m^2 Q^*$ and $v_{exh} = C_m Q^*$.)

THE DOUBLE-PULSE PLANAR LSD-WAVE THRUSTER

The double-pulse thruster cycle, first proposed by Reilly[5], can be divided into four phases: ablation, plasma ignition, LSD-wave propagation, and exhaust expansion. These are shown in figure 1.
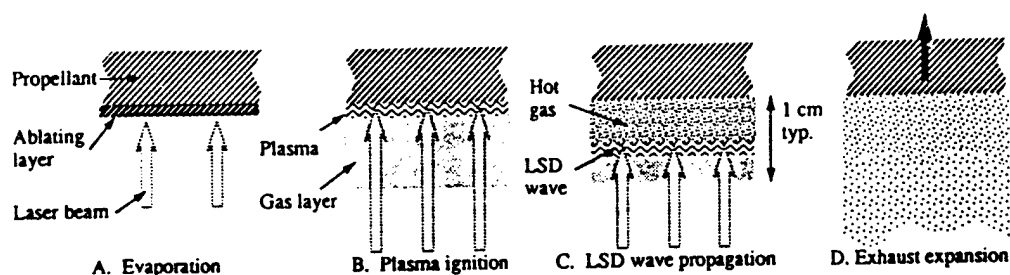
MASTER

Figure 1: Double-Pulse Thrust Cycle

During the first phase, a laser flux of typically 10^6 w/cm^2 (below the plasma ignition threshold) ablates a few-micron-thick layer of propellant (a), forming a layer of vapor which is allowed to expand to roughly atmospheric density. Key to this phase is a propellant which, in solid form, has a short absorption depth at the laser wavelength. If the absorption depth is long compared to the thickness of the evaporated layer, much of the laser energy will remain in the solid propellant and cause "dribbling" — a slow loss of propellant mass by sublimation between laser pulse pairs.

The second laser pulse propagates through the vapor layer to the solid surface. The vapor must be transparent to the laser wavelength, and cool enough to be unionized. The second pulse is at 10^7-10^8 w/cm^2, and may have a leading-edge spike of still higher flux. This high flux rapidly creates a plasma near the solid surface (b). The mechanisms that initiate such plasma formation are poorly understood and the flux and fluence needed may be quite high. For laser propulsion, we need to create an opaque plasma that shields the solid surface from the laser beam at as low a flux and fluence as possible.

Once the plasma forms, it absorbs laser energy via inverse bremsstrahlung and expands, producing a shock in the gas layer. The shock moves out from the surface (c) as a classic LSD wave at velocity $V_D = [2(\gamma^2-1)\phi/\rho]^{1/3}$, where γ is the ratio of specific heats, ϕ is the laser flux and ρ the gas density[6]. As the wave travels, it absorbs laser energy in the ionized region just behind the shock, and transfers it to the gas, leaving behind (ideally) a uniformly hot plasma, typically at 10,000 K. As the shock reached the edge of the gas layer, the laser pulse ends.

Finally, the hot gas expands (d), generating additional thrust, and cools. The impulse delivered depends on the geometry of the expansion and the chemistry of the exhaust. For a large thruster diameter D and short main pulse duration τ, the detonation wave travel $L = \tau V_D$ is small compared to D, and the expansion is essentially 1-dimensional except for small edge losses. Thrust can thus be generated efficiently without a nozzle — hence the "planar" thruster. Typical values for a real thruster are $D = 200$ cm and $L = 1$ cm ($\tau = 1$ μs), so the 1-D approximation can be very good.

The planar thruster permits an extremely simple vehicle design — essentially a block of propellant with a payload on top. It also has two additional advantages: first, the thrust direction is independent of the laser beam direction; the vehicle can fly at an angle to the laser beam, with the conical shape keeping the payload shielded from stray light. Second, the thrust can varied across the base of the vehicle by controlling the beam profile. The vehicle can therefore be steered from the ground, and does not need its own guidance system. The double-pulse cycle, by separating the ablation and heating processes, allows them to be optimized separately. This is expected to lead to higher thruster efficiency with a wider range of propellants than would be possible with single pulses. The nominal goal of the Laser Propulsion Program is $\eta_{av} = 40\%$ at 800 s I_{sp}.

STATUS OF PULSED LASER PROPULSION RESEARCH

Program research has focussed on the interaction of 10.6 μm laser pulses with a few candidate propellants. The choice of wavelength is based on the relative ease of generating and propagating long laser wavelengths, on the ready availability of laboratory CO_2 lasers for experiments, and on the properties of the thruster itself — e.g., the threshold for LSD-wave propagation varies as $1/\lambda$. However,

work with shorter wavelengths will be needed in the future to match the wavelengths of proposed large SDIO lasers.

Propellants must have a variety of properties, including strong absorption of the evaporation pulse, efficient LSD-wave ignition and propagation properties, and either low dissociation energy per gram or very rapid recombination properties. Because no single material has all the desired properties, we need to "invent" propellants by mixing different materials — e.g., adding ignition sites and low-ionization seed materials to materials with desirable optical and chemical properties.

To date, the best results have been obtained with lithium hydride, which has a low molecular weight and is easily ionized, reducing the flux needed to maintain an LSD wave. While complete dissociation of LiH requires 58.4 kJ/g, its near relatives have low dissociation energies (e.g., 16.0 kJ/g for NaH). Another class of possible propellants are polyacetal plastics (($CH_2O)_n$, trade names Delrin[tm] and Celcon[tm]). These have extremely short absorption lengths (of order 1 μm)[7] and are easy to combine with various additives. Water ice is a good candidate for full scale systems, but is inconvenient for small experiments due to its high vapor pressure and moderate absorption depth (roughly 6 μm).

Theoretical and computer modeling of the double-pulse cycle has been conducted primarily by Physical Sciences, Inc. (PSI); a portion of this work is summarized elsewhere in these Proceedings[8]. This work has focussed on 1-D modeling of the evaporation and LSD-wave propagation phases of the cycle, and on simple chemical rate models for the expansion phase. No adequate model for plasma ignition and initial growth exists, particularly for the complex propellant materials of interest, but the metal-flake ignition model of Weyl[9] has led to successful tests of 10 μm metal-coated glass beads as ignition sites in dielectric propellants[10]. Chang and Mulroy[11] have modeled the late-time expansion of the exhaust in 2-D for an ideal gas, but full nonequilibrium chemical calculations have not been done. In most cases reaction rates are not available for the species and temperatures of interest; shock-tube measurements of such rates would be valuable.

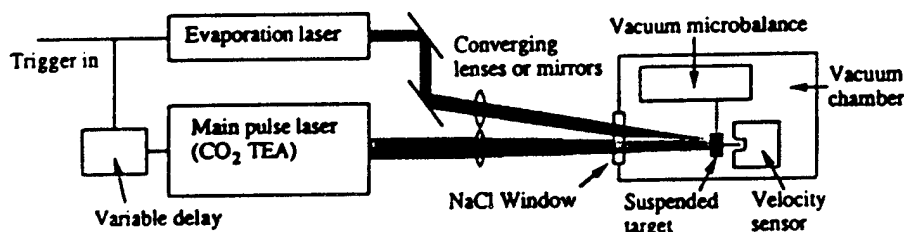The general form of experiments is shown in figure 2.

Figure 2: General form of double-pulse thruster experiments -- measuring mass removed and total impulse for various interpulse delays and pulse fluences.

Most experiments have been done with 50 to 100 ns pulses (TEA laser gain-switch spike) with energies of approximately 2 to 40 J and spot sizes of less than 1 cm^2. As the interpulse time increases from zero, one expects a minimum in the amount of mass ablated, as the gas layer produced by the first pulse reaches an appropriate density for the second pulse to produce an LSD wave which shields the surface; at long times the gas layer dissipates and the mass removal should increase again. To the extent that the laser energy is coupled into a smaller mass of gas, the exhaust velocity (specific impulse) and efficiency should peak in the same range of interpulse times where the ablated mass is minimized. Figure 3 shows results from Hale[12] in which the expected variations in ablated mass, specific impulse, and efficiency occur. These results were obtained with equal energy in the first and second pulses, with an average flux in each case of 2.5×10^{7}w/cm^2; the high first-pulse energy results from the long (14 μm[13]) absorption depth of LiH. Unfortunately, the observed peak η_{ab} and I_{sp} are only roughly 8% and 600 s, respectively, in part due to the very inefficient evaporation process. However, Reilly[14] has observed specific impulses of over 1000 seconds at efficiencies of over 10% using LiH and either single or double pulses at somewhat higher fluxes (over 10^{8}w/cm^2).
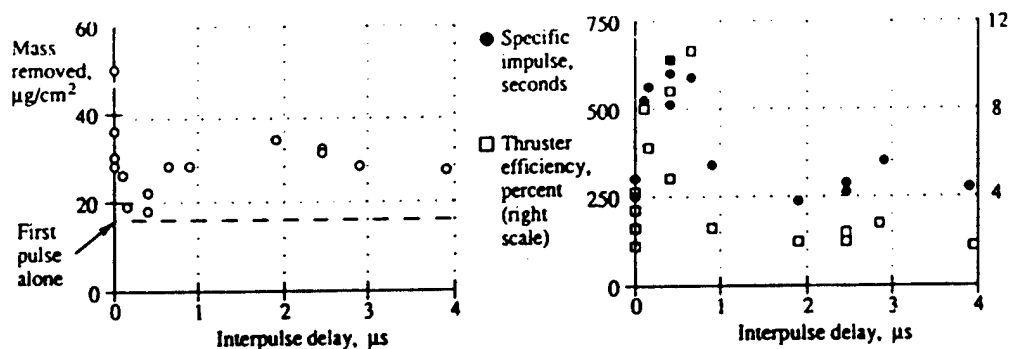
Figure 3: Experimental results, LiH target, 25 MW/cm^2 peak in each 70 ns pulse

True double-pulse operation has not yet been observed with polyacetals, despite considerable effort. Recent results from Hale[15] suggest that the problems with double pulse tests stem from a significant delay in the ablation process. Schliren measurements indicate that, for the polyacetal plastics, most of the ablated mass does not come off the surface for up to several microseconds, while the interpulse delays in the experiments have been largely less than 1 μs.

While current results are very preliminary, both theory and experiment suggest that longer laser pulses (and correspondingly higher energi⁻) will yield much better results. All phases of the cycle involve characteristic time or length scales which appear to be at best comparable to the current scales of our experiments. The Program is thus setting up larger scale experiments using 500 ns to 1 μs laser pulses at energies of 500 to 2000 J; these are expected to yield significantly higher efficiencies.

Dimpled Surfac⁻ for Air-Breathing Propulsion

A side area of research under the Laser Propulsion Program is air-breathing propulsion. In an air-breathing vehicle, laser energy must be efficiently coupled to a large volume of air to produce maximum impulse. The exhaust velocity (specific impulse) is of no concern, as the supply of reaction mass is unlimited. One approach to this coupling is the dimpled surface, suggested in a very different context by Root et al.[16], and reinvented for propulsion by this author. A dimpled surface is simply a sheet of reflective material (such as copper or aluminum) with many small concave pits or dimples formed in it. Each dimple acts as an independent focusing mirror. For reasonable incident fluxes of $10^6 - 10^7$ w/cm^2, even a crude reflector can produce fluxes at the focal point exceeding the clean air breakdown threshold of approximately 10^9 w/cm^2.

We have manufactured dimpled surfaces in copper sheet using ordinary machine tools (spherical end-mills of 3.2 to 25.4 mm diameter) to cut overlapping dimples with spacings of 0.8 to 6.4 mm and effective focal ratios of f/2 to f/0.5. These plates (figure 4) have been illuminated with CO$_2$ TEA laser pulses of approximately 1 to 6 J/cm^2 (peak fluxes $\approx 3 \times 10^6 - 2 \times 10^7$ w/cm^2). These plates produce uniform arrays of breakdowns, as shown in open-shutter photographs (figure 5). Using pinholes in the plates, we have measured transmitted laser light with a pyroelectric detector and observed the formation of breakdowns (reduction of transmission) in times as short as 10 ns, and at fluences as low as approximately 10 mJ/cm^2. By suspending the plates to form a ballistic pendulum, we have measured coupling coefficients in excess of 20 dyne-s/J on a 10 cm square flat plate (no nozzle); this is sufficient for useful air-breathing propulsion, and higher coupling coefficients should be readily obtained.

Finally, we have used a gated image intensifier/CCD camera assembly (Amperex XX1610) to obtain images of the laser-induced breakdowns above the surface with a time resolution of approximately 10 ns. A small sample of these images is reproduced in figure 6; this shows a side view of a single row of dimples, spaced 3.2 mm apart and illuminated with approximately 4 J/cm^2. These images show the initial breakdowns occurring at the dimple focal points, and the rapid growth of the luminous region toward the surface. During these times, the fluxes near the focal point are quite high, and the breakdown grows supersonically. At later times, the growth toward the surface stagnates, and the
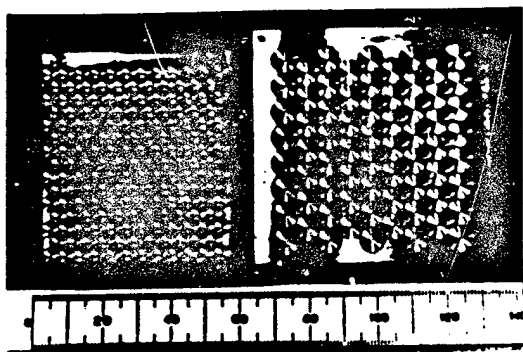
Figure 4: Dimpled surfaces machined from 1 mm copper plate (ruler scale in mm).
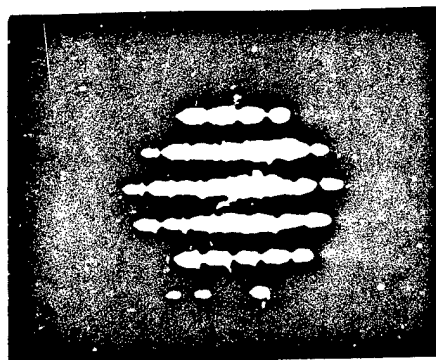

Figure 5: Open shutter exposure of breakdowns above a dimpled plate.

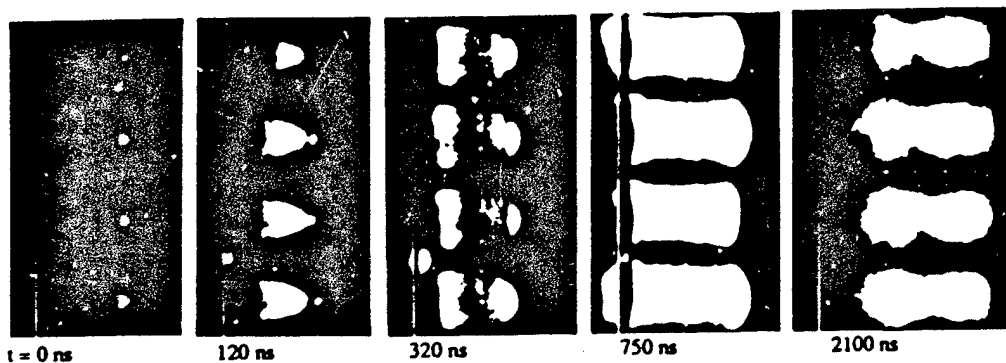| t = 0 ns | 120 ns | 320 ns | 750 ns | 2100 ns |

Figure 6: Side view of breakdowns above a row of 1.5 mm f/1 dimples at various times from start of laser pulse. Bright line is plane of dimpled surface; bright areas behind surface are reflections. Small specks are computer-generated fiducials. Laser pulse (1 μs, 4 J/cm^2) enters from right.

"upstream" side of the breakdown, driven directly by the incident laser beam, develops a separate luminous zone; the unconcentrated flux is below 10^7 w/cm^2 and the plasma grows subsonically.

There is considerable structure present in both the individual plasmas, and in their interaction. An unexpected result of these experiments has been the observation that the individual laser-sustained plasmas are very reluctant to merge into a continuous plasma, even after they have grown perpendicular to the plate by several times their center-to-center spacing. Figure 7 shows two images taken "face on" of an array of 6 mm spaced dimples, where one dimple has been deliberately blocked to prevent a breakdown. The complex patterns present suggest interesting interactions among the breakdowns. These details are very reproducible, both from dimple to dimple and from laser pulse to laser pulse.

Additional work is needed on dimpled plates, including additional diagnostics such as Schliren photography to directly image shock fronts produced. We intend to explore the behavior of dimpled surfaces under a wider range of conditions, including particularly lower air pressures, to determine their usefulness and possible performance limits for propulsion. Dimpled surfaces may prove to be useful in other areas, for example the detailed study of the breakdown process and of interacting shocks, since they provide many reproducible breakdowns in close proximity.

CONCLUSIONS

The double-pulse planar LSD-wave thruster is a very simple way to efficiently convert laser energy into rocket thrust. Preliminary experiments with 50 - 100 ns CO_2 laser pulses have demonstrated that the double-pulse cycle can enhance efficiency and specific impulse compared to single laser pulse coupling. Although best results have been obtained with lithium hydride, modeling and tests show that "invented" propellants containing various mixtures of materials can have controllable
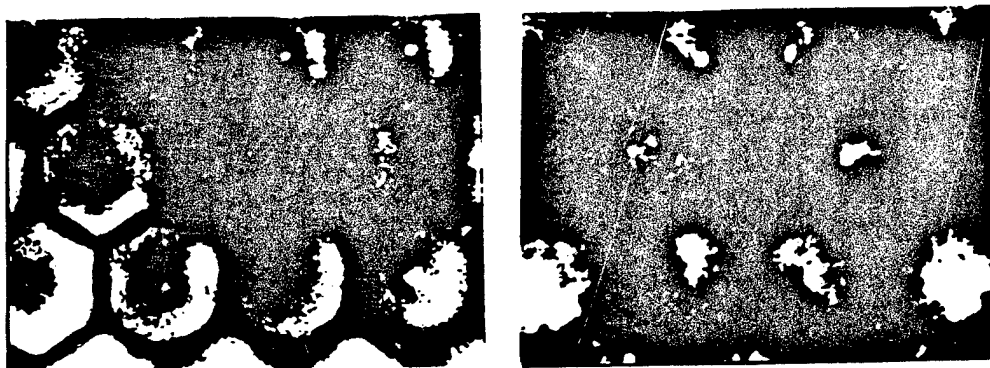
Figure 7: 6 mm f/0.5 dimples, front view, with central dimple blocked. Note structure within separate breakdowns (left, t = 2 µs) and from interactions of breakdowns (right, t = 5 µs). Laser pulse approx. 1 µs, 2 J/cm^2.

optical, ignition, and LSD-wave propagation properties. It is expected that a combination of such optimized propellants and longer-pulse, higher-energy experiments will demonstrate performance much better than the current 10% efficiency at 600 s I_{sp}.

Air-breathing laser propulsion is also possible using dimpled-plate reflectors to couple the laser energy into the air. Coupling coefficients of 20 dyne-s/J have already been demonstrated using simple machined copper plates. These plates have been observed to produce very reproducible arrays of laser-induced breakdowns, which may be useful for other research.

ACKNOWLEDGEMENTS

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